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Radial flow from the nucleus of Galaxy

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An expression for radial flow velocity of gaseous materials from the nucleus of our Galaxy, has been derived. It is found that mainly the gravitational force has the capability of controlling this flow. It is suggested that an accelerating mechanism (most probably nuclear explosion) caused the 3-*kpc* arm to move. Using the values of different parameters it is concluded that 3-*kpc* arm started its journey at about 12 million years ago with the velocity 234 *km/s*., but afterwards mainly due to gravitational pull its velocity has been reduced to 53 *km/s* at the present time.

1. Introduction

The origin and maintenance of radial flow of gas (ionised and nonionised) from the nucleus of our Galaxy are very important but undecided problems of today. The radial (outward) gas flow has a significant role in the formatign and evolution of the structure of the Galaxy. It directly associates itself with the gas distribution in the region (1–4) *kpc* from the centre, and also with the mass content of the nucleus (Woltjer 1965, Keer & Westerhout 1965, Oort 1971).

The gas flow can be described upto a very good approximation by the fluid equation, namely,

$$\rho[\partial/\partial t+(\boldsymbol{v}.\Delta)]\boldsymbol{v} = -\Delta p-\rho\Delta\phi-(1/8\pi))\Delta B^2+(1/4\pi)(\boldsymbol{B}.\Delta)\boldsymbol{B}, \quad \ldots \quad (1)$$

where $\boldsymbol{v}$ is fluid velocity, $\boldsymbol{B}$ the magnetic field, ρ the density, p the gas pressure and ϕ the gravitational potential. Furthermore, the pressure p is related with the density through the relation.

$$p = C_0^2\rho \quad \ldots \quad (2)$$

C_0 being the sound speed. As we know, in general, the complete description of the fluid flow requires two more equations, namely equation of continuity and the field equation (Spitzer 1968, Woltjer 1965). However, in the present paper we have not used the last two equations. Making some assumptions we have obtained the expression for radial flow.

Many authors (Woltjer 1965, van der Kruit 1970, Oort 1971) have put forward a convincing physical model of expanding 3-*kpc* arm of our Galaxy.

According to them an explosion in the nucleus of Galaxy about 13 million years ago is the source of present expanding arms at 3 *kpc*. The present analysis desires to put more or less similar model of the 3-*kpc* expanding arms, using the basic fluid equation. Using the numerical values of the parameters involved we have simplified the momentum equation and found that mainly it is the gravitation which determines the expansion of the arm. Eventually we are led to conclude that the 3-*kpc* arm obtained its present day expansion velocity by some accelerating mechanism (may be nuclear expansion) which occurred 12 million years ago, before producing an initial velocity 234 *km/s*. Afterwards, the said arm has been decelerated uptill now so that the velocity of the arm has now become 53 *km/s*.

2. Simplification of the Basic Equation

Let us consider the physical situation where the motion is mainly concentrated on a $(r-\theta)$ plane. Further let us assume that

(A) all the field variables are radially symmetric.

Then we have from eq. (1)

$$\frac{\partial v_r}{\partial t}+v_r\frac{\partial v_r}{\partial r}=-\frac{1}{\rho}\left(C_0^2\frac{\partial \rho}{\partial r}+\rho\frac{\partial \phi}{\partial r}\right)-\frac{B_\theta}{4\pi\rho}\frac{\partial B_\theta}{\partial r}, \quad \ldots \quad (3.1)$$

$$\frac{\partial v_\theta}{\partial t}+v_r\frac{\partial v_\theta}{\partial r}=\frac{B_r}{4\pi\rho}\frac{\partial B_\theta}{\partial r}, \quad \ldots \quad (3.2)$$

where the subscript r and θ denote the component in those directions respectively.

We now make some assumptions (required by the physical conditions of the medium considered in the present paper, see next section), namely

(B) The temporal variation of the velocity is much greater than the spatial variation of the same, so that,

$$\partial v/\partial t >> v\partial v/\partial r.$$

(C) The spatial variation of the magnetic field is much smaller than the spatial variation of other parameters like ρ and ϕ.

Therefore, eqs. (3.1) and (3.2) reduce to

$$\partial v_r/\partial t = -\rho^{-1}(C_0^2\partial\rho/\partial r+\rho\partial\phi/\partial r), \quad \ldots \quad (4.1)$$

$$v_\theta = \text{constant (independent of time)}. \quad \ldots \quad (4.2)$$

If now we assume that

(D) the parameters ρ, C_0, ϕ, and their derivatives remain constant in a time interval $[0, t]$ then we have

$$v_{rt} - v_{r0} = -\rho^{-1}(C_0^2 \partial\rho/\partial r + \rho\partial\phi/\partial r)t, \qquad \ldots (5.1)$$

$$v_\theta = \text{Constant}. \qquad \ldots (5.2)$$

The most important (and relevant to our present discussion) point regarding the velocity of the above motion is that it is only radial velocity which increases with time in the medium where both density and potential decreases spatially as the distance from the centre increases.

3. Radial Flow in 3-kpc Arm of Our Galaxy

Almost all the observations so far made have led us to believe that in a galactic plane the motion and density upto the region of 3-*kpc* arm are almost radially symmetric. Therefore, the assumption (A) may be safely valid at (1–4) *kpc* from the Galactic centre.

There are very good observational reports, still believed to be correct, put forward by Rougoor & Oort (1960). According to them the radial flow of gas well inside the 3-*kpc* arm (say, at 1 *kpc* region) is $\sim$150 km sec^{-1}, and at 3 *kpc* arm it is $\sim$53 km sec^{-1}. Therefore, at 3-*kpc* region we can take approximately

$$v_r \frac{\partial v_r}{\partial r} \sim 53 \times 10^5 \frac{(150-63)\times 10^5}{2\times 3{\cdot}09\times 10^{21}} \approx 8\times 10^{-9}(\text{C.G.S. unit}).$$

Further, it is suggested by many authors that the 3-*kpc* arm is being accelerated (Woltjer 1965). According to the present author this may be very useful suggestion. We assume that the temporal variation of radial flow is much greater than 8×10^{-9} (C.G.S. unit) i.e.,

$$\frac{\partial v}{\partial t} >> 8\times 10^{-9}(\text{C.G.S}).$$

This means that if T is the characteristic time of variation of radial velocita v_r, then

$$T << v_r \times 10^9/8 \sim 2\times 10^7 \text{ yrs}.$$

Thus the assumption that radial flow velocity changes over the time period which is much less than 20 million years, is equivalent to the assumption (B) already made in deriving the relation (5.1).

It is suggested for the maintenance of the gas flow from the centre that the magnetic field strength may be of the order 8×10^{-5} gauss inside in nucleus and 5×10^{-6} gauss in the central region (1–4) *kpc*, and 2×10^{-6} gauss near local region (Woltjer 1965). The actual observations reveal a definite weaker field strength on the Galactic disk $\sim(3-5)\times 10^{-6}$ gauss (Parker 1970). Apart from the magnitude of the weak field strength one must note that the spatial variation of the magnetic field is too small to be encountered. Let us assume that inside the central region (1–4) *kpc.*, the variation of the field strength is $\sim 2\times 10^{-6}$ gauss *kpc.*, and the field strength is $\sim 5\times 10^{-6}$ gauss. Then the third term on the r.h.s. of eq. (3.1) or first term on the r.h.s. of eq. (3.2) is $\sim 2{\cdot}5\times 10^{-34}$ (C.G.S.).

According to Schmidt's model (1965) the density variation is given by the curve (figure 1). The slope of the curve $(\rho - r)$ at about 3·4 *kpc* is given by density

$$\partial\rho/\partial r \sim 1{\cdot}15\times 10^{-44} \text{ (C.G.S.)}.$$

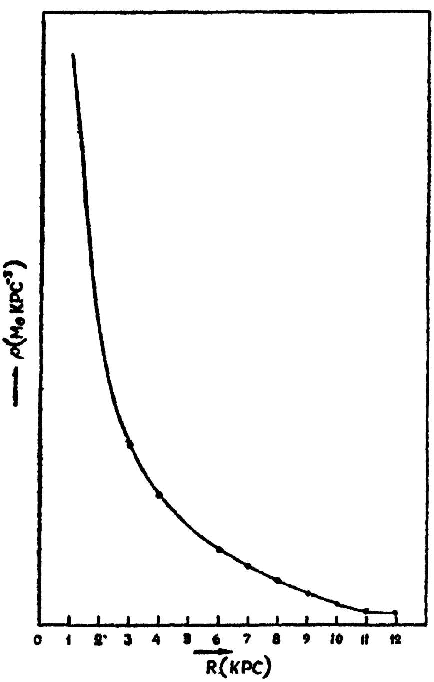

Fig. 1. Density curve (Unit of vertical length = 0.2×10^{9} $M_{\odot}$Kpc^{-3})

The gaseous material flowing radially in the 3-*kpc* arm are supposed to be partially non-ionised (H–I) and partially ionised (H–II). The sound speed for the H–I region and H–II region may be taken as 1·2 km sec^{-1} and 14 km.sec^{-1} respectively (Kaplan 1966). Therefore,

$$C_0^2\,\frac{\partial\rho}{\partial r} \sim \begin{cases} 1{\cdot}7\times 10^{-34} \text{ (for H–I)} \\ 2{\cdot}2\times 10^{-32} \text{ (for H–II)}. \end{cases}$$

We can observe, therefore, that for H–I region the first and third terms of r.h.s. of eq. (3.1) are of same order. So that we can omit the third term by simply making the first term double. However, for H–II region the third term on the r.h.s. of eq. (3.1) may be neglected.

Thus, if the parameters C_0, ρ, ϕ are constant in a time interval, the radial velocity in the 3-*kpc* region is given by, from (5.1),

$$|v_r| \cdot \begin{cases} \rho^{-1}(2C_0^2\partial\rho/\partial r + \rho\partial\phi/\partial r)t & \text{(for H–I region)} \quad \ldots \quad (6.1) \\ \rho^{-1}(C_0^2\partial\rho/\partial r + \rho\partial\phi/\partial r)t & \text{(for H–II region).} \quad \ldots \quad (6.2) \end{cases}$$

It-is suggested by many authors (Burbige & Hoyle 1963, Woltjer 1965, van der Kruit 1970, Oort 1971) that the outward radial gas motion in 3-*kpc* arm can be explained if we take it to be granted that an explosion had occurred inside the nucleus at about 13 million years ago, and that stage lasted about a million years. Let us suppose that the present density and potential distribution remained constant throughout 12 gillion years. Then the first parts of the expression (6.1) and (6.2) give

$$|v_r| \sim 0{\cdot}014 \text{ kg/s (for H–I)}$$

$$|v_r| \sim 1{\cdot}000 \text{ km/s (for H–II)}$$

clearly these results are much less than the observed radial velocity ($\sim$53 ng/s) of the 3-*kpc* arm. Therefore, for the particular case we are considering, the radial velocity is given by, from eq, (5.1),

$$v_{rt} = v_{r0} - t\partial\phi/\partial r, \tag{7}$$

for both H–I and H–II regions. Now, $\partial\phi/\partial r$ represents the force of attractiog on the moving mass element of unit mass due to other masses. The spiral arms outside 3-*kpc* arm are cooparatively at larger distances than the distances where masses of the rogion (0–3) *kpc* are present. Furthermore, the amount of mass contained within this region may be taken as 20% of the total mass of the Galaxy (see the discussion at the end of this section). Therefore the principal contribution to the force of attraction exerted on 3-*kpc* are is due to the mass present in the region (0–3) *kpc*. Let this mass be denoted by M. Then the radial velocity is give by

$$v_{0t} = v_{r0} - tCM/R^2, \tag{8}$$

where R is the distagce of the moving mass element from the Galactic centre. In general, this formula may be useful for finding out the radial velocity where the gravitational force has predominating role. Since the gravitat,on is very effective in all astrophysical situations one can exbect that formula (8) will be able to enplain the radial flow of the gaseous material. Let us now return to our original problem of finding out the radial velocity of 3-*kpc* arm (situated at about 3·4 *kpc*). From eq. (8), it is given by

$$v_{rt} \approx v_{r_0} - 6 \times 10^{-52} tM \qquad \text{(C.G.S. unit).} \qquad = \quad (9)$$

Taking, $t = 12 \times 10^6$ yrs., we obtain

$$v_{rt} \approx v_{r_0} - 2{\cdot}28 \times 10^{-37} M \qquad \text{(C.G.S. unit).} \qquad (10)$$

One can find that the radial velocity of 3-*kpc* arm can be determined if one knows the amount of mass which exerts gravitational, force on it. Let us suppose that this amount of mass be 20% of the total mass of the Galaxy (*i.e.*, $M \sim 8 \times 10^{43}$ gms), then

$$v_{rt} \; [illegible]_0 - 1{\cdot}81 \times 10^7) \qquad \text{[C.G.S. unit].}$$

It is to be noted that the mass of the nuclear disk of radius ($\sim 20\ pc$) is $\sim 3{\cdot}10^8\ M_0$ (Woltjer 1965, Oort 1971). The mass of the central mass point of radius 500 *pc* is often taken as 3.5% of the total mass of the Galaxy, and that of the spheroid of radius $\sim 10 kpc$ is taken as 41% of the total mass of the Galaxy (Schmidt 1965). Therefore, it will be quite logical to take the mass of the material which being situated inside the 3*kpc* arm, and being capable of exerting gravitational force, as 20% of the total mass of the Galaxy.

4. Discussions

van der Kruit (1970) suggested that the location and radial outward motion of the 3-*kpc* arm could be explained if about 13 million years ago gas was expelled from the nucleus at angles between 25° and 30° with the galactic plane, with velocities which at $R = 100\ pc$ were about 500 km.sec^{-1}. A considerable part of this gas would at the present time have fallen back to the galactic plane between 3–4 *kpc* from the centre and have been decelerated by the original quiescent gas layer, so that the outward radial component has become about 50 km/s.

In the theory presented here we have shown that if the density and potential distribution does not change appreciably throughout last 12 million years then the radial velocity of 3-*kpc* arm at present is given by

$$v_{rt} = (v_{r_0} - 181) \text{ km.sec,}^{-1}$$

where v_{r_0} is the initial radial velocity expressed in km/s. It is evident therefore, that to have a radial velocity about 53 km/s at the present time, the 3-*kpc* arm might have a initial velocity 234 km/s. It is important to note that Woltjer (1965) suggested roughly an initial velocity 250 km/s with which the 3-*kpc* arm had started its journey at about 10^7 years ago, which has close resemblance with the numerical values obtained by the present author. Thus we are led to conclude that at about 12 million years ago there was a mechanism which caused the

3-*kpc* arm to move with initial velocity 234 km/s. One might have seen in the previous section that the magnetic field or density gradient cannot affect the radial motion of 3-*kpc* arm significantly. It is only the gravitation which is able to reduce this velocity effectively so that the present day radial velocity has become 53 km/s. It is to be noted that in the Schematical model proposed by van der Kruit (1970) it was assumed that once the gases are outside the sphere of radius 100 *pc* the motion of them would be governed soloely by the gravitational, field upto the time when they fall into the galactic layer. According to our analysis (eq. 7) the radial motion of the 3-*kpc* arm is still being governed mainly by gravitational force of the mass interior to the spiral arm, during last 12 million years.

5. Determination of the Mass of the System

Throughout the above discussion one might have noticed that the maximum uncertainty lies in the numerical values of M (the amount of mass exerting gravitational force) and t (duration of time so long as the basic distribution of density and potential remains unaltered). Therefore, sometimes it may be worthwhile to determine M or t because the other paramoters are, in general, can be determined from experimental observations. In particular the mass determination is a very important problem. There are some standard methods of determining the mass of the Galaxies (Schmidt 1965, Basu & Roy 1973). One can observe that if the physical conditions are such that all the assumptions (A) to (D) hold good, and further if the gravitational force has the predominating role on the mass motion then from (4.1) we can write

$$M = (R^2/G)\,(\partial v\,/\partial t). \qquad \dots (10)$$

Therefore, if the non-vanishing radial acceleration component is determined then the total amount of mass which exerts gravitational force on the moving mass, can be found out from eq. (10). However, we desire to discuss this problem in a different paper.

6. Conclusions

It is realised that the complete interpretations of the equations derived, have not been given. We have concentrated ourselves only to the problem of finding the radial gas flow.

Due to large amount of uncertainty the numerical estimations may have to be modified. But still the formulae seems to be very useful to explain the radial gas flow upto a good approximation.

The origin and maintenance of large scale spiral structure of Galaxy are very important problems. The maintenance problem, however, is satisfactorily solved by density wave theory (Lin, Yuan & Shu 1969). In connection with the present paper it may be worthwhile to mention that the origin of large scale spiral structure may have some good correlations with the explosion and radial flow from the nucleus, which occurred about 12 million years ago. For example, it may be interesting to investigate whether the gravitational disturbances produced due to said explosion have any role in determining the spiral structure.

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